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Linear and passive silicon optical isolator

Chen Wang, Xiao-Lan Zhong & Zhi-Yuan Li

Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences, P. O. Box 603, Beijing 100190, China.

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Correspondence and requests for materials should be addressed to Z.-Y.L. (lizy@aphy.iphy.ac.cn)

On-chip optical isolation plays a key role in optical communications and computing based on silicon integrated photonic structures and has attracted great attentions for long years. Recently there have appeared hot controversies upon whether isolation of light can be realized via linear and passive photonic structures. Here we demonstrate optical isolation of infrared light in purely linear and passive silicon photonic structures. Both numerical simulations and experimental measurements show that the round-trip transmissivity of in-plane infrared light across a silicon photonic crystal slab heterojunction diode could be two orders of magnitudes smaller than the forward transmissivity at around 1,550 nm with a bandwidth of about 50 nm, indicating good performance of optical isolation. The occurrence of in-plane light isolation is attributed to the information dissipation due to off-plane and side-way scattering and selective modal conversion in the multiple-channel structure and has no conflict with the reciprocal principle.

Isolation of light is fundamental in information processing[1]. It provides critical functionalities such as optical isolation and circulation in photonic systems. Although widely used in lasers and optical communications, such devices are still lacking in semiconductor integrated photonic systems because of challenges in both materials integration and device design[2–4]. Conventionally, an isolator is a two-port device that transmits microwave or radio frequency power in one direction only. It is used to shield equipment on its input side, from the effects of conditions on its output side; for example, to prevent a microwave source being detuned by a mismatched load. An efficient routine to create optical isolation is via time-reversal symmetry breaking[5,6]. Up to now several schemes have been implemented to break reciprocity, including magneto-optical isolators[7–9], nonlinear optical structures[10,11], and time-dependent optical structures[12,13].

However, practical applications of these approaches are limited for the silicon photonics because of their incompatibility with conventional CMOS processing, which have demonstrated generating, modulating, processing and detecting light signals for next-generation optical communications[14–16]. In 2011 several groups reported on-chip silicon diodes in the regime of time-reversal symmetry breaking. Ross's group uses traditional magnetism to construct isolators by monolithically integrating a phase-pure polycrystalline $(Ce_1Y_2)Fe_5O_{12}$ (Ce:YIG) films on silicon[17]. Their diode has good isolation signal but highly depends on the external magnetic field which could influence other devices near the diode. Qi's group reports an on-chip optical diode by using the optical nonlinearity of silicon[18]. Their diode is truly passive without external field, but has disadvantages such as large loss of isolation signal (at least -35dB loss), a relatively large size, and slow response due to the usage of high-Q ring resonators.

Recently several schemes to realize unidirectional transport of light through linear and passive photonic structures have been proposed[19–21], which are essentially based on the principle of spatial-inversion symmetry breaking. Feng *et al.* reports a passive silicon optical diode based on one-way guided mode conversion[20]. However, whether or not nonreciprocal transport of light can happen in the structure has raised hot controversies[22,23]. Fan *et al.* made a scattering matrix analysis for relevant forward and backward modes of the structure and argued that the structure is essentially reciprocal and cannot enable optical isolation because it possesses a symmetric coupling scattering matrix. In their response, Feng *et al.* acknowledge that their structure, as a one-way mode converter with asymmetric mode conversion, is Lorentz reciprocal, which states that the relationship between an oscillating current and the resulting electric field is unchanged if one interchanges the points where the current is placed and where the field is measured, and on its own cannot be used as the basis of an optical isolator. The controversies have thus raised a fundamental question: Can one construct an optical isolator by using a linear and time-independent optical system? The answer to this question by the authors of Ref. 22,23 obviously is no.

Unidirectional transport of light occurs in a device wherever the forward and backward transmissivity of light is very much different. Very recently, we reported an ultrasmall on-chip optical diode based on silicon photonic crystal (PC) slab heterojunction structures[21]. The optical diode is linear, passive, and time-independent, but has a spatial-inversion symmetry breaking geometry. It is made from the heterojunction between two different silicon two-dimensional (2D) square-lattice PC slabs with mismatch in directional bandgap and unidirectional mode

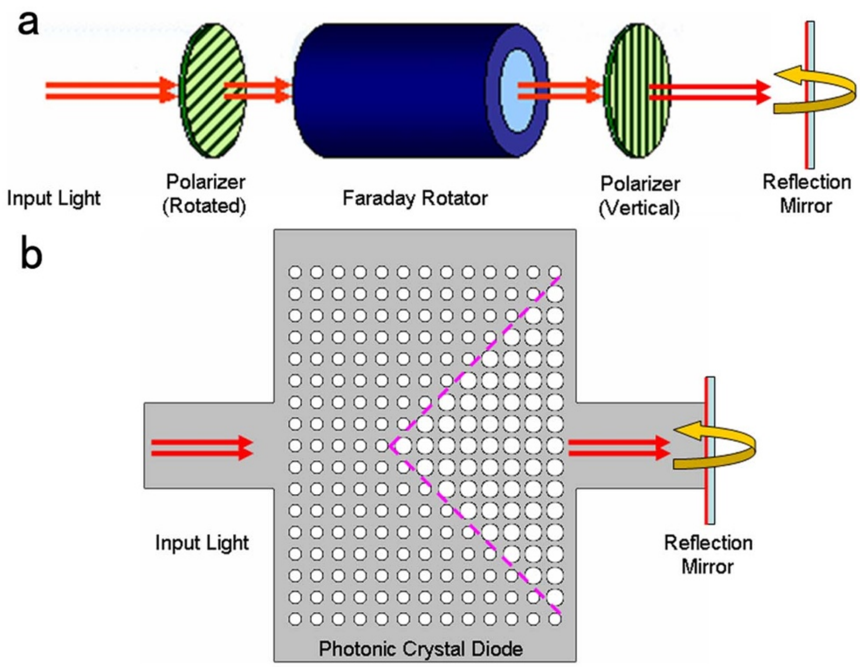

Figure 1 | (a) Traditional magnetic-optical isolator with a reflection mirror at the output port. (b) On-chip optical diode system with a reflection mirror at the output port. The absence of the reflection signal at the input port can indicate the isolation property of the system.

transitions. The geometry of the diode structure is not symmetric with respect to the middle plane of the optical diode in the transport direction, including the two photonic crystals comprising the hetero-junction, and the input and output waveguides. The maximum forward transmissivity in experiment approaches 21.3% and the best signal contrast of the diode structure reaches 0.885 at the peak, which is near the value of present electrical diodes. The overall size of the ultrasmall diode is 6×6 μm². Both theory and experiment show an obvious significant unidirectional infrared light transport in the silicon diode without time-reversal symmetry breaking. Our theoretical and experimental study on the optical isolation performance of this silicon PC heterojunction diode leads to a totally different answer to the above question, namely, the spatial inversion symmetry breaking diode can construct an optical isolator in no conflict with any reciprocal principle.

Results

To see whether there is a good isolation effect of the silicon diode, we implement a direct method that is originated from the conventional magneto-optical isolator popularly used in laser devices [Fig. 1(a)]. One places a total reflection mirror after the output port in the forward direction of the isolator device and monitor the reflection signal from the input port [Fig. 1(b)]. This reflection signal well describes and measures the round-trip transmissivity of light across the isolator device. If the reflection signal is the same as or is comparable with the forward signal, then the structure does not have the desired isolation property. In contrast, if the reflection signal is much smaller than the forward signal, then a good isolation property is implied.

An equivalent way to investigate the optical isolation performance of the diode structure is to adopt a doubled-diode structure with a mirror-symmetrical plane located at the forward direction output port of the diode, as depicted in Fig. 2. Obviously this method has set all the forward output signals as the backward input signal of the diode and thus can directly test the isolation property of the diode structure. By implementing this method, we calculate simultaneously the forward transmissivity and the round-trip transmissivity of the diode structure by using three-dimensional finite-difference

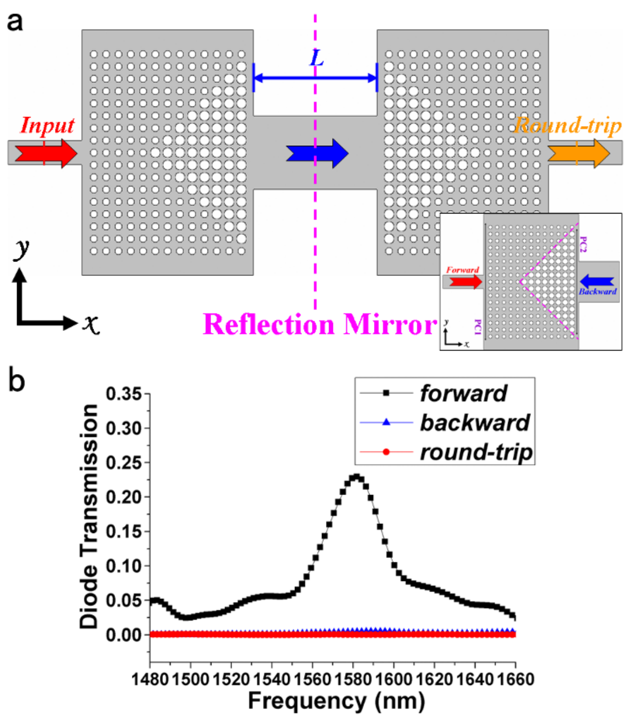

Figure 2 | (a) Schematic geometry of a doubled-diode structure with a mirror-reflection symmetry with respect to the total reflection mirror, which is used to model the round-trip transmission of an isolator. Inset is the corresponding single-diode structure where the forward and backward transmissions are noted. (b) Calculated forward (black line), backward (blue line), and round-trip (red line) transmission spectra of the diode. The performance of the optical isolator is evaluated by comparing the round-trip transmissivity with the forward transmissivity. Our calculation shows that the former is more than two orders of magnitudes smaller than the latter.

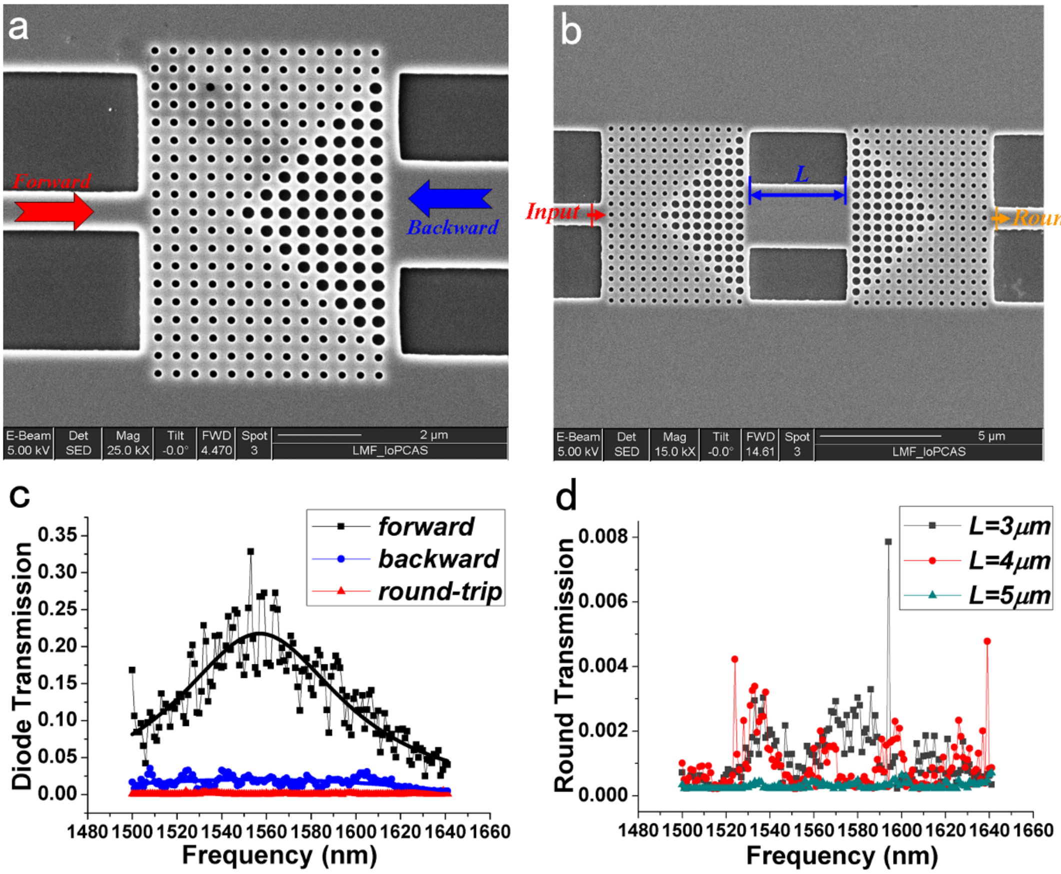

Figure 3 | (a) Scanning electron microscope images of our on-chip optical diode structure and (b) doubled-diode structure. (c) Experimental results of the forward (black line), backward (blue line), and round-trip (red line) transmission spectra. (d) Experimental round-trip transmission spectra with changed length L of the center connection waveguide. The experiment confirms the existence of a significant isolation effect in agreement with the theoretical prediction.

time-domain (3D-FDTD) method. Comparison of these two quantities would directly measure the isolation properties.

Figure 2(a) is the schematic geometry of the doubled-diode structure corresponding to the diode depicted in Fig. 1(b). The width of the input and round-trip output waveguides is the same 2***a*** (***a*** =440 nm is the lattice constant) and the center connection waveguide is 6***a***. The length of the center connection waveguide, which measures the distance of the total-reflection mirror away from the output port of the diode, is 10***a***. The schematic geometry of the single diode structure used to calculate the forward and backward transmission spectra, which contains the same input/output ridge waveguide as well as only one single diode structure, is depicted in the inset of Fig. 2(a). The light source is placed at the input port with 2***a***-wide ridge waveguides connecting the surface of the diode region. The whole area is surrounded by a perfectly matched layer. The calculated spectra [Fig. 2(b)] show that the round-trip transmission peak is located at 1,582 nm and has a quantity of only 0.3%, which is almost two orders of magnitude smaller than the forward peak [with a maximum transmissivity of 22.9%]. The result indicates that the diode has a significant optical isolation property.

Based on the above numerical analysis, the double-diode structure was fabricated in silicon. The pattern was first defined in resist using the electron beam lithography on the top layer of a silicon-on-insulator (SOI) chip. The resist pattern was then transferred to silicon layer using the inductive coupled plasma reactive ion etching (ICP-RIE) technique. The insulator layer (SiO_2) underneath the silicon pattern regions was finally removed by a HF solution to form an air-bridged structure. Figures 3(a) and 3(b) show the scanning electron microscopy images of the fabricated single diode and double-diode structures along the light path. The lattice constant ***a*** was 440 nm, the radii r_1 and r_2 of air holes in the two photonic crystals of the heterojunction diode were approximately 110 nm and 160 nm, respectively. The length of the center connection waveguide is 4 μm (≈10***a***). The slab thickness was 220 nm. To measure the transmission spectra, infrared light from a semiconductor laser, which is tunable between 1,500 nm and 1,640 nm, was directly coupled into the PC heterojunction diode with the aid of tapered ridge waveguides in the input and output ends[27]. The backward transmissions is measured the same as the forward and round-trip transmissions except switching the input and output ports.

Figure 3(c) shows the experimentally measured forward and backward transmission spectra of the diode, as well as the round-trip transmission spectrum of the doubled-diode structure. The forward, backward and round-trip transmissions are optimized and the input/output loss has been removed against a reference sample. The spectra show that the maximum round-trip transmissivity, located at 1,553 nm, is below 0.5%, almost two orders of magnitude smaller than the forward peak [with a maximum transmissivity of 32.9%]. The experimental peak in Fig. 3(c) has a near 30 nm shift and 50 nm broadening against the theoretical simulations [Fig. 2(b)], which is probably due to the imperfections in fabrication. The experiment confirms the existence of a significant isolation effect in agreement with the theoretical prediction. We change the length of the center connection waveguide of the double-diode structure from 4 μm to 3 μm and 5 μm. The measured round-trip transmission spectra for the three structures are displayed in Fig. 3(d). The results show that the round-trip transmission signal decreases remarkably along with the increasing length of the center connection waveguide, and already

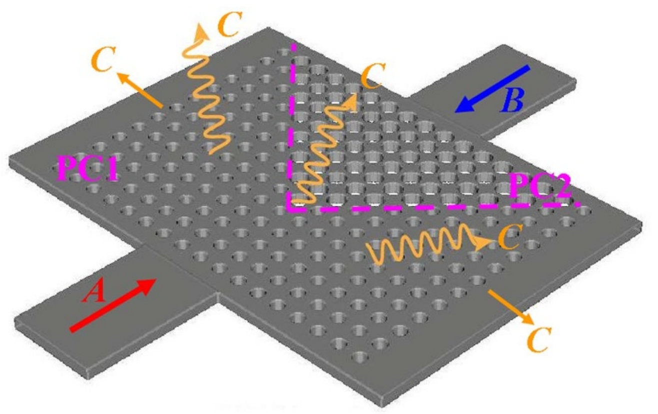

Figure 4 | Schematic geometry of the diode structure as shown in Fig. 1(b) for multiple-channel mode scattering and conversion analysis. The system involves in-plane signal channel A and B, and in-plane side-way and off-plane dissipation channels C. The latter one holds the key to optical isolation.

reaches an extremely low level (below 0.05%) in the whole spectrum range when the output waveguide length increases to 5 μm. This clearly indicates that the mode dispersion in the output waveguide of the diode has no influence to the isolation property of the diode. Due to the arbitrariness of the lattice constant **a**, we can freely adjust the isolation frequency to anywhere as desired. This could be very convenient for the design of realistic photonic devices.

Discussion

To better understand the underlying physics, we further make a detailed analyses based on the scattering matrix theory adopted in Ref. 22,23, and find that the above numerical results of optical isolation are in no conflict with the reciprocity theorem involved in the linear and passive silicon optical diode structure. As is depicted in Fig. 4, our diode basically consists of two in-plane information channels (A and B, the input and output waveguide channels for infrared signal, which can be either single mode or multimode channels.) as well as many in-plane side-way and off-plane scattering channels (denoted as C as a whole, which causes dissipation of information away from the signal channels). At the two ends of the diode device the fields are written as follows:

$$\begin{bmatrix} A_{out} \\ B_{out} \\ C_{out} \end{bmatrix} = S \begin{bmatrix} A_{in} \\ B_{in} \\ C_{in} \end{bmatrix}, \qquad (1)$$

in which $A_{\rm in}$ corresponds to the input signal from port A, $A_{\rm out}$ to the output signal from port A, $B_{\rm in}$ to the input signal from port B, $B_{\rm out}$ to the output signal from port B, $C_{\rm in}$ to the input signal from port C, and $C_{\rm out}$ to the output signal from port C. The scattering matrix S transforms the input state of all the channels [the column vector in the right hand of Eq. (1)] into the output state of all the channels [the column vector in the left hand of Eq. (1)]. In the case of forward transport of infrared signal across the diode with an input signal $\boldsymbol{a}_{\rm in0}$ at port A, the reflection signal $\boldsymbol{a}_{\rm out1}$ is very small compared with the transmission signal $\boldsymbol{b}_{\rm out1}$ or the scattering signal $\boldsymbol{c}_{\rm out1}$ according to our numerical simulation results[21]. Then the scattering equation for the forward transmission is approximately written as:

$$\begin{bmatrix} a_{out1} \\ b_{out1} \\ c_{out1} \end{bmatrix} = S \begin{bmatrix} a_{in0} \\ 0 \\ 0 \end{bmatrix}. \qquad (2)$$

As the silicon diode structure is linear and passive, the system as a whole is reciprocal in regard to time-reversal symmetry following the Lorentz reciprocity theorem. As a result, the scattering matrix S symmetric ($S = S^T$) and further satisfies energy conservation[22–26]:

$$S^* = S^{-1}. \qquad (3)$$

Suppose all the output signals are reversed and come back into the system, then the input at port B for the system is now exactly the same as $[\,a^*_{out1} \quad b^*_{out1} \quad c^*_{out1}\,]^T$. The scattering equation is then

$$S \begin{bmatrix} a^*_{out1} \\ b^*_{out1} \\ c^*_{out1} \end{bmatrix} = (S^* \begin{bmatrix} a_{out1} \\ b_{out1} \\ c_{out1} \end{bmatrix})^* = (S^{-1} \begin{bmatrix} a_{out1} \\ b_{out1} \\ c_{out1} \end{bmatrix})^* = \begin{bmatrix} a^*_{in0} \\ 0 \\ 0 \end{bmatrix}, \qquad (4)$$

which is exactly the same as the initial input from port A. This clearly indicates that there is no isolation behavior in the structure if all information is reversed back into the system, consistent with the reciprocity theorem for a time-reversal symmetric system.

However, the story can be very different when only the in-plane signal transport is concerned, as is always the case for 2D silicon PC slab structures. In our structure the information and energy involved in C channels are dissipated permanently against the in-plane channel A and B due to scattering loss (both in-plane and off-plane), and they cannot be reversed back totally and input again into the structure, so in practice, $C_{\rm in}$ in Eq. (1) can be assumed to be zero. As a result, Eq. (4) should be modified as:

$$S \begin{bmatrix} 0 \\ b^*_{out1} \\ 0 \end{bmatrix} = \begin{bmatrix} a_{out2} \\ b_{out2} \\ c_{out2} \end{bmatrix}. \qquad (5)$$

In general, Eq. (5) looks very different from Eq. (4), which indicates that the reciprocal transport of light in regard to the signal channel A and B has been broken. It shows that even if the same forward transmission signal of port B is reversed back and input into the diode, the output signal of port A can be much different from the initial input signal $\mathbf{a}_{\rm in0}$ of port A because no signal is reversed and input back into the channel C. Therefore, the considerable unidirectional transmission behavior can take place for the in-plane signal with no conflict with the reciprocal principle. In other words, $a_{out2}(=S_{12}\bullet b^*_{out1})$ could be much different from $a^*_{in0}(=S_{11}\bullet a^*_{out1} + S_{12}\bullet b^*_{out1} + S_{13}\bullet c^*_{out1})$ when $S_{11}\bullet a^*_{out1} + S_{13}\bullet c^*_{out1} \neq 0$. This justifies the occurrence of a good isolation effect in the silicon optical diode. In ideal structures, both quantities are zero, and Eq. (5) becomes

$$S \begin{bmatrix} 0 \\ b^*_{out1} \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ c_{out2} \end{bmatrix}, \qquad (6)$$

which implies a 100% signal contrast of the isolator.

As an example, we consider the scattering matrix S of our diode in the case of maximum forward transmission. The quantities of S-matrix element are calculated based on the mode-to-mode transmission coefficients T_{ij}, where $T_{ij} = S^2_{ij}$. The results are $S_{11} = -0.321$, $S_{22} = -0.732$, $S_{33} = -0.255$, $S_{12} = 0.462$, $S_{13} = 0.827$, $S_{23} = 0.501$, and $S_{ij} = S_{ji}$. It can be easily found that the backward in-plane reflection ($T_{22} = 0.536$) is much larger than the forward in-plane reflection ($T_{11} = 0.103$), in consistence with the existence of directional band gap in PC2. The scattering loss in both forward and backward directions are quite large, with $T_{13} = 0.684$ and $T_{23} = 0.251$, indicating the existence of strong scattering loss channels. With these quantities, we find that the round-trip amplitude a_{out2} ($=0.213$) is very different from the input one $a^*_{in0}(=1)$, confirming the unidirectional transport of the diode as analyzed in the above.

According to our simulations and experiments for our silicon optical diode, our diode has not only two in-plane signal channels but also many other scattering channels. In this linear and passive structure, the working channels are only two selected channels among the multiple channels. The other unselected channels can help the structure to break the spatial inversion symmetry without changing the circumstance of symmetric scattering matrix, as these channels cannot reverse the output signals back into the structure. As a result, significant unidirectional transport of light can occur in the signal channels in no conflict with reciprocal principle. Simply speaking, it is the selective mode conversion in a multiple-channel structure that comprises the basis of optical isolation in our passive, linear, and time-independent silicon optical diode. More important, this selective mode conversion is intrinsic of the silicon structure itself, and does not require external manipulation and perturbation that is requested by all existing time-reversal symmetry breaking schemes.

The above physical picture can also be used to evaluate the optical isolation performance of other unidirectional photonic structures. In the scheme of the asymmetric mode-conversion waveguide diode structure as discussed in Ref. 20, the system has only two channels: one input and one output channel (each involving one even and one odd mode). During the transport, scattering and modal conversion process of light across the diode structure, as well as the reflection process of light with respect to a mirror, all light signals are contained within the channels and the signal dissipation to other channels does not exist. As a result, the mode conversion of the system must be reciprocal under the circumstance of the symmetric scattering matrix. In the scheme of 2D photonic crystal gratings where a significant one-way transmission effect has been demonstrated theoretically[19], our calculation [Fig. S1 in the supplemental materials] shows that the round-trip transmission signal is nearly the same as the forward transmission signal in the unidirectional-transport frequency regime where the backward transmission is much lower than the forward transmission. This strongly indicates that the unidirectional-transport photonic crystal grating does not have the true isolation property. Another example is the multimode interference filter (MMIF) which is well-known in the photonics community[28]. As the same, the MMIF system may have the unidirectional transport property. But if we send the same output signal back into a MMIF system, the round-trip transmission signal would be the same as the forward transmission signal following the Lorentz reciprocal theorem, due to the lack of the open loss channels. This again indicates that the unidirectional transport MMIF system does not have the true isolation property. The reason is also simple. Although each of the two structures involves multiple channels of signal, all output signals are reversed and input back into the system itself by a total-reflection mirror, leading to a reciprocal transport of light.

It is worth saying a few more words here for better drawing a clear picture about the physics discussed in the above. In nature, as time always flows forward and cannot be reversed, one usually uses the term of reciprocal or nonreciprocal transport of light to describe a model system of back transport of light, in many cases to describe the reflection of light back into the considered structure. In this regard, simply consider a point source radiating an outgoing spherical wave front. If time can be reversed, the outgoing spherical wave front is contracted into an ingoing spherical wave front, eventually to a point. This is a very good picture to describe reciprocal transport of light in a linear system. However, to realize in real world such a concept, one needs to place a perfect spherical mirror concentric with the point source of light, which reflects back all information carried by the outgoing expanding spherical wave into the ingoing contracting spherical wave. If, however, one has only a small planar mirror placed at some distance and with a limited solid angle with respect to the source, the reflected signal can never return to the initial state of a point source when it reaches the position where the light source is located. The conventional magneto-optical isolator also works in this category of physical picture. It is used to block down the back-reflection signal of the transmission light, and the underlying physics can be well described by the model of time-reversal symmetry breaking. The same physics picture applies equally well to our optical diode. The fact that there exists information dissipation from the signal channels to other channels in a spatial-inversion symmetry breaking structure is sufficient to induce optical isolation in regard to the signal.

In summary, our numerical calculations and experimental results show that our silicon PC slab heterojunction diode exhibits promising performance of optical isolation, with a round-trip transmissivity two orders of magnitude smaller than the forward transmissivity for the in-plane infrared light across the structure. Our scattering matrix analysis indicates that the considerable unidirectional transport of in-plane signal light can be attributed to the information dissipation and selective modal conversion in the multiple-channel spatial-inversion symmetry breaking structure and has no conflict with reciprocal principle for a time-reversal symmetric structure. It is expected that optimized connection interfaces between the input and output waveguides with the heterojunction diode can yield better impedance mismatch and bring higher forward transmission efficiency. That optical isolation can occur in a linear, passive, and time-independent optical structure would stimulate more thinkings and insights on the general transport theory of light in the fundamental side and open up a road towards photonic logics in silicon integrated optical devices and circuits in the application side.

Methods

Simulation. We use 3D-FDTD method for numerical simulation on the transmission spectra and field patterns. The doubled-diode structure is used to calculate the round-trip transmission spectrum and the single diode structure is used to calculate the forward and backward transmission spectra, which all contain the same input/output ridge waveguide. The width of the input and round-trip output waveguides is the same $2\boldsymbol{a}$ ($\boldsymbol{a}$ =440 nm is the lattice constant) and the center connection waveguide is $6\boldsymbol{a}$. The length of the center connection waveguide is $10\boldsymbol{a}$. The grid size used in the simulation is 11 nm. The light source is placed at the input port with $2\boldsymbol{a}$-wide ridge waveguides connecting the surface of the diode region and the receiving plane is placed at the output port. The whole area is surrounded by a perfectly matched layer.

Sample fabrication. The patterns were first defined in resist using the electron beam lithography (EBL) on the top layer of a silicon-on-insulator (SOI) chip. The resist patterns were then transferred to silicon layer using the inductive coupled plasma reactive ion etching (ICP-RIE) technique. The insulator layer (SiO_2) underneath the silicon pattern regions was finally removed by a HF solution to form an air-bridged structure.

Measurements. In our optical experiments, light from a semiconductor laser, which is tunable between 1,500 nm and 1,640 nm, was directly coupled from a single mode tapered fiber into the input ridge waveguides at the input port. And at the output port, a single mode tapered fiber was used to attach the output ridge waveguides and the power meter by direct coupling. We also measured the transmission power of the reference waveguide, which had only the same tapered ridge waveguides but no diode region. The loss from the input fiber to the output fiber is −20 dB.

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Author contributions
Z.Y.L. designed the study, C.W. and X.L.Z. performed the numerical simulations, C.W. fabricated the samples, collected, and analyzed the data. Z.Y.L. and C.W. wrote the paper. All authors discussed the results and commented on the manuscript.

Additional information
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